

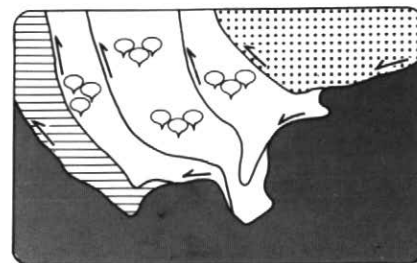
overtaken hornblende isograd in the footwall of the out-of-sequence domain (Figure 1; Bégin, 1989 - this issue, p. 151-154).

#### Acknowledgements

Normand Bégin and Dave Scott (Queen's University) are both thanked for numerous discussions on all aspects of the Cape Smith Belt. Mauricio Bonardi (Geological Survey of Canada) ensured an efficient microprobing environment during the course of this study. Christian Picard improved a first version of this paper.

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## Shear zone softening at the base of the Cape Smith Belt: implications for the rheological evolution of thrust belts<sup>1</sup>

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#### Summary

The rheological and structural consequences of thrust belt metamorphism have been studied using both numerical thermal-rheological models and field and thin-section observations on ductile thrust zones in the Early Proterozoic Cape Smith Thrust Belt. Development of these ductile thrust zones had several important consequences for the evolution of the thrust belt: (1) penetrative bulk shear deformation of both hanging wall and footwall units leading to the development of mylonitic foliations; and (2) movement on a restricted number of relatively large displacement thrusts. Relatively broad ductile shear zones developed adjacent to thrusts during prograde metamorphism in order to accommodate movement on the thrusts, while relatively narrow shear zones developed adjacent to thrusts during retrograde metamorphism. The results of both the field studies and the thermal-rheological models suggest that temperature- (and time-) dependent weakening processes are strongly accentuated by lithological contrasts.

#### Résumé

Les conséquences du métamorphisme régional dans la bande du Cap Smith d'âge Protérozoïque inférieur ont été analysées d'une part à l'aide des observations de terrain et de l'étude de lames minces prélevées dans les zones de chevauchements plastiques et d'autre part à l'aide de modèles numériques thermo-rhéologiques. La formation des zones de chevauchements plastiques a eu plusieurs conséquences im-

<sup>1</sup> Geological Survey of Canada Contribution No. 19089

portantes sur l'évolution de la ceinture de chevauchement. Premièrement, un cisaillement en vrac des compartiments supérieurs et inférieurs des failles chevauchantes a entraîné la formation de mylonites. Deuxièmement, le transport tectonique a suivi un petit nombre de failles chevauchantes à forts rejets. Des zones relativement épaisses de cisaillement plastique se sont formées à proximité des failles chevauchantes au cours du métamorphisme prograde afin d'accueillir le mouvement de ces failles. Par contre, des zones de cisaillement relativement étroites se sont formées de manière tangentielle aux failles chevauchantes durant le métamorphisme retrograde. Les résultats des travaux de terrain et des modèles thermo-rhéologiques indiquent que la formation des zones de faiblesse qui dépendent des facteurs température et temps, est fortement favorisée par des contrastes lithologiques.

**Introduction**

Metamorphism of thickened crust in an active thrust belt has significant consequences for the rheology of the belt, and thus its structural evolution. The rheological evolution of a thrust belt and its footwall is strongly influenced by thermally activated softening processes (Poirier, 1980; White *et al.*, 1980). Development of ductile thrust zones as a result of these processes can localize deformation at the scale of the thrust belt, leading to the accumulation of significant displacements along these zones. An example of this is the shear zone which developed on the hanging wall of the Main Central Thrust during crustal-scale thrusting in the Himalayas (Bouchez and Pêcher, 1981; Brunel, 1986).

In this paper, the development of ductile shear zones which accommodate thrust motion below the brittle-ductile transition is studied using two independent approaches. First, field and thin-section observations are used to constrain the principal factors which contributed to the growth of ductile shear zones in the Early Proterozoic Cape Smith Thrust Belt (St-Onge and Lucas, in press). The second approach involves the construction of kinematically and thermally constrained rheological models in order to study the gross rheological evolution the Cape Smith Belt. Preliminary results of some of these models are presented in the second half of this paper.

**Structural and Metamorphic Evolution of the Thrust Belt**

The Cape Smith Thrust Belt developed in response to northward underthrusting of the Superior Province continental margin (Lucas, in press). The thrust belt is composed chiefly of imbricated rift, transitional crust and ophiolitic suite rocks of Early Proterozoic age (St-Onge and Lucas, in press; Picard *et al.*, in prep.; St-Onge *et al.*, 1989 - this issue, p. 119-122). Early thrusting produced a 20 to 30 km-thick thrust stack above a basal décollement localized at the contact between the Early Proterozoic cover units and the Archean basement of the Superior Province (Figure 1). Thermal equilibration of the thrust stack resulted in greenschist- to amphibolite-grade metamorphism (Bégin, 1989 - this issue, p. 151-154; St-Onge and Lucas, 1989 - this issue, p. 154-158). As a consequence of heating of the thrust belt, ductile shear zones developed adjacent to thrust faults and décollements ("ductile thrusts") in order to accommodate their

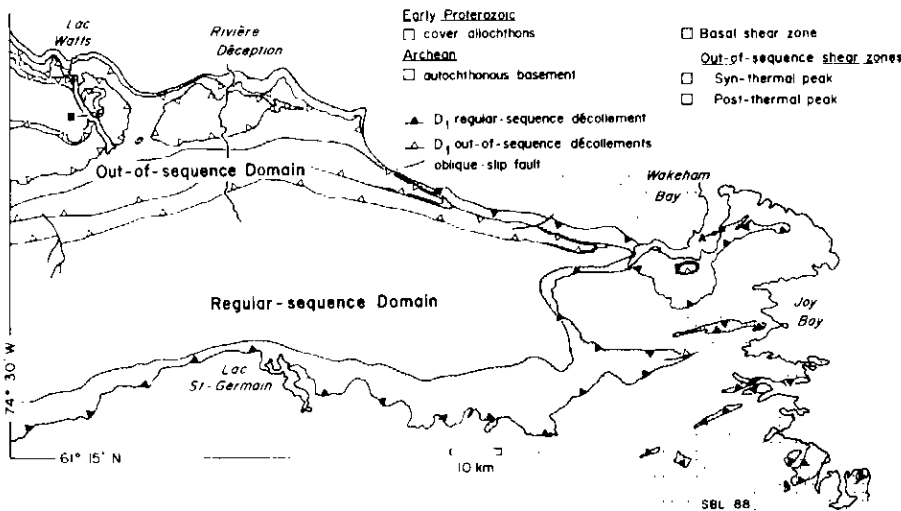
movement (see Figure 1 for the distribution of shear zones; Lucas, in prep.).

The ductile shear zones are divided into a prograde group and a retrograde group depending on the nature of the syn-deformation metamorphism. The prograde shear zones include both the relatively early basal shear zone and the later syn-thermal peak shear zones related to out-of-sequence thrusting (Lucas, in press; Lucas and St-Onge, 1989 - this issue, p. 122-126). The basal shear zone developed adjacent to the basal décollement in both the thrust belt and its footwall during pre-thermal peak deformation, but ceased movement at syn-thermal peak conditions when it was overridden by out-of-sequence thrusts (Figure 1). The shear zones developed adjacent to these out-of-sequence thrusts record syn-thermal peak movement (Figure 1). Retrograde shear zones include (1) footwall Archean gneisses which were reworked during prograde deformation in the overlying thrust belt; and (2) shear zones developed in the hanging walls of post-thermal peak, out-of-sequence thrusts. The following two sections will focus on the processes associated with the development of prograde and retrograde shear zones.

**Prograde Shear Zones**

Several processes contributed to the development of the foliations associated with the prograde shear zones: (1) a thermally activated switch to dislocation creep in quartz (from pressure solution) and feldspar (from grain-scale fracturing) (e.g., Tullis and Yund, 1985, 1987); (2) prograde metamorphic reactions; and (3) the formation of compositional layering. These processes can produce both hardening and softening effects which will compete to determine a shear zone's bulk rheology. As an example, the softening effect of oriented mineral growth ("geometric softening"; Poirier, 1980; White *et al.*, 1980) during prograde metamorphic reactions probably competes against the hardening effect of reactions which produce stronger products than reactants (e.g., Brodie and Rutter, 1985). However, the very presence of the prograde shear zones (Figure 1) suggests that, at the scale of the thrust belt, softening processes probably predominated over hardening effects.

The development of compositional layering (e.g., Robin, 1979) during syn-metamorphic deformation may produce a bulk weakening if (1) shear strain is partitioned into relatively weak layers (Bell, 1981), and (2) the strong layers are able to accommodate the weak layer deformation (e.g., through boudinage). Compositional layering in thrust belt rocks was either formed (e.g., in basalts) or enhanced (e.g., in mafic cumulates, Figure 2) during the prograde bulk shear deformation. An example of the development of compositional layering leading to



**Figure 1** Map illustrating the extent of ductile shear zones which accommodated movement on thrust faults. Two geometrically and temporally distinct domains of thrust faults are recognized (Lucas and St-Onge, 1989 - this issue, p. 122-126): the relatively early regular-sequence domain, and the relatively late out-of-sequence domain.

strain partitioning is shown in Figure 2; hornblende and plagioclase-zoisite layers are forming, and the deformation is being accommodated largely by the plagioclase-zoisite layers.

### Retrograde Shear Zones

A retrograde mylonitic foliation developed in high-grade footwall gneisses during deformation associated with the overlying prograde shear zones. Metamorphism of the basement gneisses is characterized by a retrogression of the Archean upper amphibolite-grade assemblage to greenschist and lower amphibolite facies assemblages. This was accomplished by the breakdown of feldspars and hornblende, and the growth of retrograde white mica, biotite and chlorite (Figure 3) and, rarely, garnet. The growth of hydrous phases indicates that retrogression of the basement gneisses probably resulted from an influx of fluids. The presence of deformed quartz veins in the basement shear zones suggests that these fluids may have been introduced into the basement from dehydrating cover rocks above the décollement. The mica-producing reactions appear to have resulted in a bulk weakening of the retrograded gneisses (Lucas, in prep.), and facilitated their bulk shear deformation (e.g., Figure 3). Ductile deformation of quartz and feldspar contributed to grain size reduction and the development of mylonitic foliations in the retrograded footwall gneisses.

Relatively narrow shear zones (1 to 10 m) occur adjacent to the post-thermal peak out-of-sequence thrusts, in contrast to the kilometre-scale shear zones which developed during prograde metamorphism. Extensively retrogressed mylonite derived from ophiolite suite rocks characterizes these shear zones. Thin-section observations (Lucas, in prep.) suggest that the weakening process primarily responsible for the relatively narrow shear zones is retrograde reactions which produce weaker and finer grained products (e.g., actinolite, chlorite) than reactants (e.g., hornblende). The post-thermal peak bulk shear deformation resulted in heterogeneous strain of the hanging wall thrust sheets (extent indicated in



**Figure 2** Compositional layering developed in a prograde metamorphic shear zone. Photograph from near location B in Figure 1.

Figure 1) in addition to the narrow shear zones. The heterogeneous strain is marked by a retrograde foliation developed along small-scale shear bands (e.g., White *et al.*, 1980) which rework the syn-thermal peak foliation. Partial replacement of amphibolite-grade assemblages by greenschist-grade minerals (Bégin, 1989 - this issue, p. 151-154) occurs along the mm- to m-scale shear bands.

### Thermal-Rheological Model

Numerical models have been constructed to solve for the flow stress associated with the dominant deformation mechanism as a function of depth (P, T) and time. Simple kinematic relationships describe the deformation of material points in thrust belt columns in order to accomplish (1) translation along a basal décollement, (2) thickening above the décollement, and (3) erosion as a function of topographic relief. The thickening is accomplished by thrusting, initially in a piggyback fashion (0-28 Ma) and subsequently in an out-of-sequence (overstep) fashion (29-39 Ma). The thermal structure of the deforming columns is determined at each timestep by solving the transient heat conduction equation (see Table 1). The Crank-Nicholson implicit finite difference method is employed for all derivatives, with the resulting matrix inversion problem solved by Gaussian elimination (Smith, 1978). The results are illustrated in Figure 4 (see also St-Onge and Lucas, 1989 - this issue, p. 154-158).

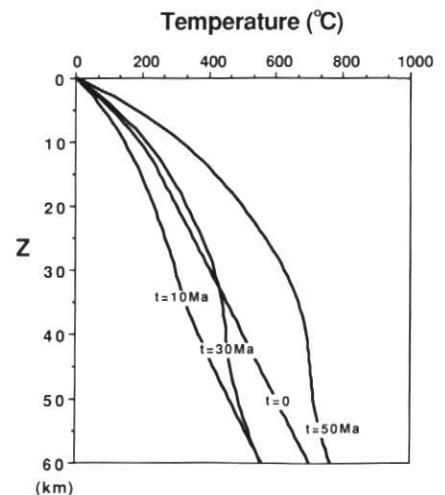
The variation in flow stress ( $\sigma_1 - \sigma_3$ ) with depth is determined at each timestep by computing the difference in principal stresses ( $\sigma_1 - \sigma_3 = \sigma_x - \sigma_z$ ). Principal stress differences are calculated for each grid point in the column using the constitutive flow law which corresponds to the dominant deformation mechanism of the thrust belt lithology at the specific P-T conditions. Only



**Figure 3** Optical photomicrograph of muscovite and biotite as retrograde metamorphic products in a reworked Archean basement gneiss below the basal décollement. The phyllosilicates define a C/S fabric (horizontal C-planes, S-planes dipping to the left) which indicates a top-to-the-south sense of displacement for the rocks. Sample collected northwest of lac Watts just below the basement-cover contact.

two deformation mechanism regimes are considered in the model: an upper brittle regime corresponding to deformation by frictional sliding along faults (Byerlee's Law, see Table 2); and a lower ductile regime corresponding to deformation by dislocation creep processes (Table 2). The thermal model provides a temperature array at each timestep which is necessary to solve the ductile flow law. The model's lithologically layered crust, set up to simulate the overall Cape Smith Thrust Belt structure, consists of a thrust belt of mafic volcanic and intrusive rocks underlain by quartz-rich sediments, and a footwall basement of granite (see Figure 5). These lithologies were modelled with experimentally derived dislocation creep flow laws (Table 2) for diabase (Shelton and Tullis, 1981; Caristan, 1982), quartzite (Kronenberg and Tullis, 1984), and aplite (Shelton and Tullis, 1981), respectively.

The inclusion of a lithologically stratified lithosphere in the model is important because many important rheological contrasts (and hence possible weak zones) within the lithosphere may occur at compositional boundaries (Ranalli and Murphy, 1987). For a lithologically layered thrust belt (diabase/quartz/aplite) with average (continental) values of thermal, kinematic and erosional parameters, the brittle-ductile transition is initially found at the diabase-quartzite interface (10 Ma, Figure 5). It subsequently moves upward into the diabase layer of the thrust belt, concurrent with a drastic drop in the strength of the quartzite and aplite (50 Ma, Figure 5). It is important to note that constitutive flow laws employed in this study are based on available experimental rock deformation studies, and greatly simplify how the continental lithosphere deforms under applied stress. Field evidence, such as the presence of a pre-existing gneissosity which is only locally reworked, suggests that the gneissic basement should be much



**Figure 4** Temperature (T) versus depth (z) plot illustrating the results of the thermal model.

Table 1 Parameters for numerical heat conduction model.

**Transient Heat Conduction Equation:** (after England and Thompson, 1984)

$$\frac{\partial T}{\partial t} = \kappa \left[ \frac{\partial^2 T}{\partial z^2} \right] + U(z,t) \left[ \frac{\partial T}{\partial z} \right] + \kappa \left[ \frac{h(z)}{K} \right]$$

where  $\kappa$ =thermal diffusivity

$K$ =thermal conductivity

$U$ =vertical velocity of a material point (erosion rate)

$h$ = depth-dependent radiogenic heat production

**Boundary Conditions:**

Surface:

$$(1) T(0) = 0$$

Base of Lithosphere:

$$(2) T(z_{\max}) = T_m$$

(3) Constant Conductive Heat Flux From Mantle

$$\left. \frac{\partial T}{\partial z} \right|_{z=z_{\max}} = \frac{q_m}{K}$$

**Erosional Parameters:**

$$\text{Erosion Rate} = E \cdot H$$

where  $E$ =Erosional Constant ( $=0.3 \text{ Ma}^{-1}$ )

$H$ =Topography (defined by Airy isostasy)

**Thermal Parameters:**

(A) Radiogenic Heat Production Rate:

Thrust Belt (Basalt>Sediment):  $0.2 \text{ Wm}^{-3}$

Footwall Basement (Tonalite Gneiss):  $2.0 \text{ Wm}^{-3}$

(B) Mantle Heat Flux/Thermal Conductivity:  $10.0 \text{ K} \cdot \text{km}^{-1}$

(C) Fixed Temperature at Base of Lithosphere:  $1300^\circ\text{C}$

(D) Initial Lithospheric Thickness: 120 km

(E) Thermal Diffusivity:  $9.0 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$

(F) Thermal Conductivity:  $2.25 \text{ Wm}^{-1} \text{ K}^{-1}$

stronger than indicated by the model results. Given the limitations of the model, the results in Figure 5 do illustrate the critical point that rheological contrasts at major lithological boundaries can play important roles in influencing the structural evolution of thrust belts.

#### Discussion

Grain-scale observations show that both softening and hardening mechanisms competed to determine the bulk rheology of the shear zones (ductile thrusts) in the Cape Smith

Belt. In a general sense, the existence of the ductile shear zones argues that softening processes probably predominated and resulted in the development of the "localized" (at the scale of the thrust belt) deformation zones. In detail, relatively broad shear zones develop adjacent to thrusts during prograde metamorphism, suggesting that the shear zone rheology is controlled by the competition between softening and hardening processes. Important softening processes active during prograde bulk shear

deformation probably included: (1) thermally activated transitions to dislocation creep mechanisms in quartz and feldspars; (2) development of compositional layering; and (3) geometric softening. In contrast, relatively narrow shear zones develop adjacent to thrusts during retrograde metamorphism. Their width is largely limited by the extent of fluid influx (necessary for retrograde metamorphism), while the shear zone rheology appears to be principally controlled by the weakening effect of retrograde reactions.

**Table 2 Parameters for rheological models.**

#### Brittle Flow Law: (after Brace and Kohlstedt, 1980)

$$(\sigma_1 - \sigma_3) = 3.9 \sigma_3 \quad \sigma_3 < 120 \text{ MPa}$$

$$(\sigma_1 - \sigma_3) = 2.1 \sigma_3 + 210 \quad \sigma_3 > 120 \text{ MPa}$$

$$\text{Effective Vertical Stress: } \sigma_z = \sigma_3 = \rho_c g z (1 - \lambda)$$

$$\lambda = 0.36$$

#### Ductile Flow Law: (after Brace and Kohlstedt, 1980)

$$\left[ \sigma_z - \sigma_x \right] = \left[ \frac{\dot{\epsilon}}{A} \right]^{1/n} e^{[Q/nRT]} \quad (14)$$

where  $\epsilon$  = strain rate =  $10^{-14}$  /sec

T = temperature

A, n, Q = Experimentally-derived flow law constants

	<u>A</u>	<u>n</u>	<u>Q</u>	<u>References</u>
<u>Diabase</u>	$2.0 \times 10^{-4} \text{ MPa}^{-n} \text{ s}^{-1}$	3.2	268 KJ/mol	Shelton and Tullis, 1981; Caristan, 1982
<u>Quartzite (wet)</u>	$1.6 \times 10^{-5}$	2.6	134	Kronenberg and Tullis, 1984
<u>Aplite</u>	$2.5 \times 10^{-7}$	3.1	163	Shelton and Tullis, 1981

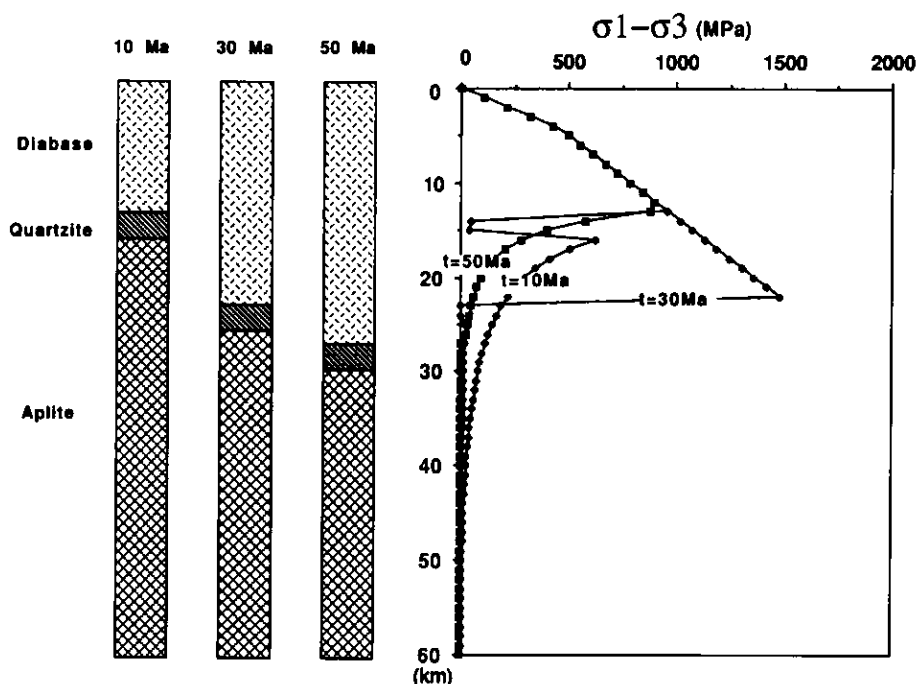


Figure 5 Flow stress ( $\sigma_1 - \sigma_3$ ) versus depth plot for the lithologically layered thrust belt shown on the left, and corresponding to the numerically derived thermal arrays illustrated in Figure 4.

A principal conclusion of the observational studies is that strength contrasts between different lithologies were probably the principal factor in controlling the distribution of deformation in the thrust belt. Strain was partitioned into the basal shear zone primarily because it was localized in relatively weak sediments sandwiched between overlying basalts and underlying basement gneisses. This conclusion is supported by the results of the thermal-rheological modelling which show that temperature- (and hence time-) dependent weakening processes are accentuated by lithological contrasts.

#### Acknowledgements

Dave Scott and Normand Bégin (both at Queen's University, Kingston) are gratefully acknowledged for their assistance both with mapping in eastern Cape Smith Belt (1985-87) and with discussions on the structural history of the belt. Tim Byrne and Jan Tullis (Brown University) are thanked for many helpful discussions and comments on the ideas presented in this paper. Christian Picard (Mineral Exploration Research Institute in Montréal) is acknowledged for his critical review.

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